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Integrated Quantum information science with photons

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Quantum information science has shown that harnessing quantum mechanical effects can dramatically improve performance for certain tasks in communication, computation and measurement. Already a number of photonic quantum circuits [1] have been realized for quantum metrology, lithography and quantum logic gates. However, these demonstrations have relied on large-scale (bulk) optical elements bolted to large optical tables, thereby making them inherently unscalable and confining them to the research laboratory. We report the implementation of quantum optic integrated circuits, which not only dramatically reduces the footprint of quantum circuits, but allows unprecedented stability and control of the optical path length; this reveals the possibility for realizing previously unfeasible large scale quantum circuits.

Figure 1A shows a schematic of an integrated quantum device composed by one coupler fabricated using the silica on silicon technology. To demonstrate quantum operation of integrated beam splitters we launched single photons into the two input waveguides of a 50:50 directional coupler. In figure 1B we show the variation of coincidences as a function of the separation between the two photons. The curve clearly shows the expected dip, with a raw visibility of $V = 94.8 \pm 0.5\%$ [2]. Besides single photons operation, Quantum Information requires universal two qubit gates such as the CNOT gate. We integrated into an optical circuit the scheme proposed by Ralph and colleagues [3, 4]. To characterize the performance of the gate, we measured the output outcomes for each of the input states in the computational basis and obtain an average local fidelity $F = 94.3 \pm 0.3\%$.

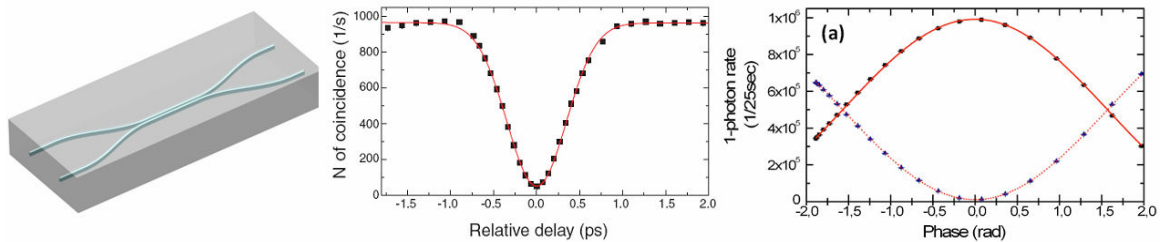


Fig.1. A: Schematic of an integrated directional coupler. B: Quantum interference in an integrated coupler. The plot shows the rate of detecting single-photons at each output of the coupler as the relative delay in arrival time of the photons is varied. C: Single photon count rates at the two outputs of a Mach-Zehnder interferometer as the phase is varied.

The ability to actively prepare and measure arbitrary single qubit states is key for the successful implementation of many quantum information systems. We designed and measured integrated waveguide Mach-Zehnder interferometers, composed by two Hadamard operations and a phase controller implemented using a resistive heater on the top of the waveguide. This device contains all the components for arbitrary one-qubit unitary operations, including state preparation and measurement. We report in figure 1C the interference pattern of single photons detected at the two outputs of the circuit when a single photons are launched into the chip. Such demonstration of “classical” interference at the single photon level demonstrates the accuracy with which single qubits can be controlled. The ability to accurately control single photon states, and generate entangled states on-chip opens the way to accurate manipulation of more general quantum states of light, for quantum information and quantum metrology [5].

We also report the results from femtosecond laser directly-written quantum circuits; devices fabricated using a laser materials-processing technique that is rapid, requires no lithographic step and is inherently 3- dimensionally compatible [6]. A large range of chip-scale “photonic building blocks” have been realized using this so-called *direct-write* technique and they include single or multimode optical interconnects, directional couplers and interferometers. The *directly written quantum circuits* exhibited high 2 and 3-photon Hong-Ou-Mandel (HOM) interference visibilities of $95.8\% \pm 0.5$ and $84\% \pm 3\%$ respectively.

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